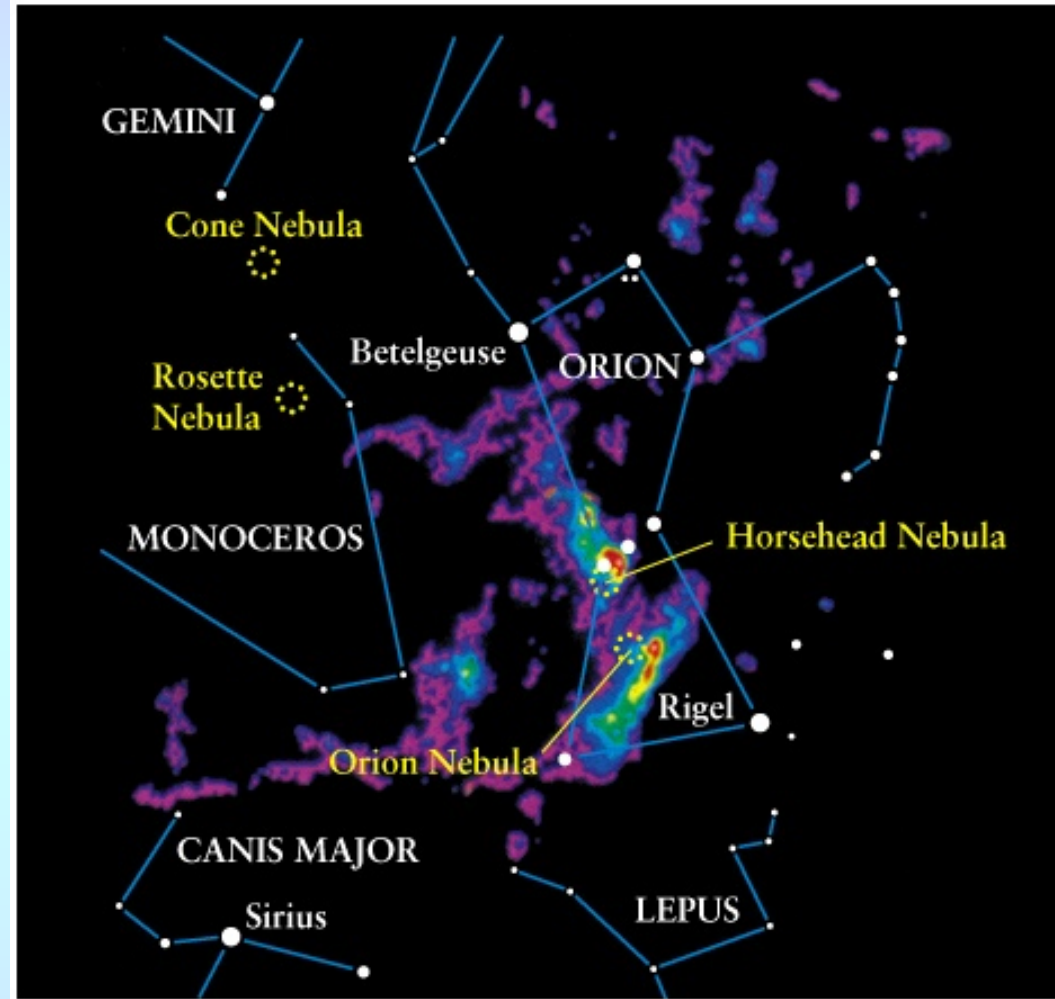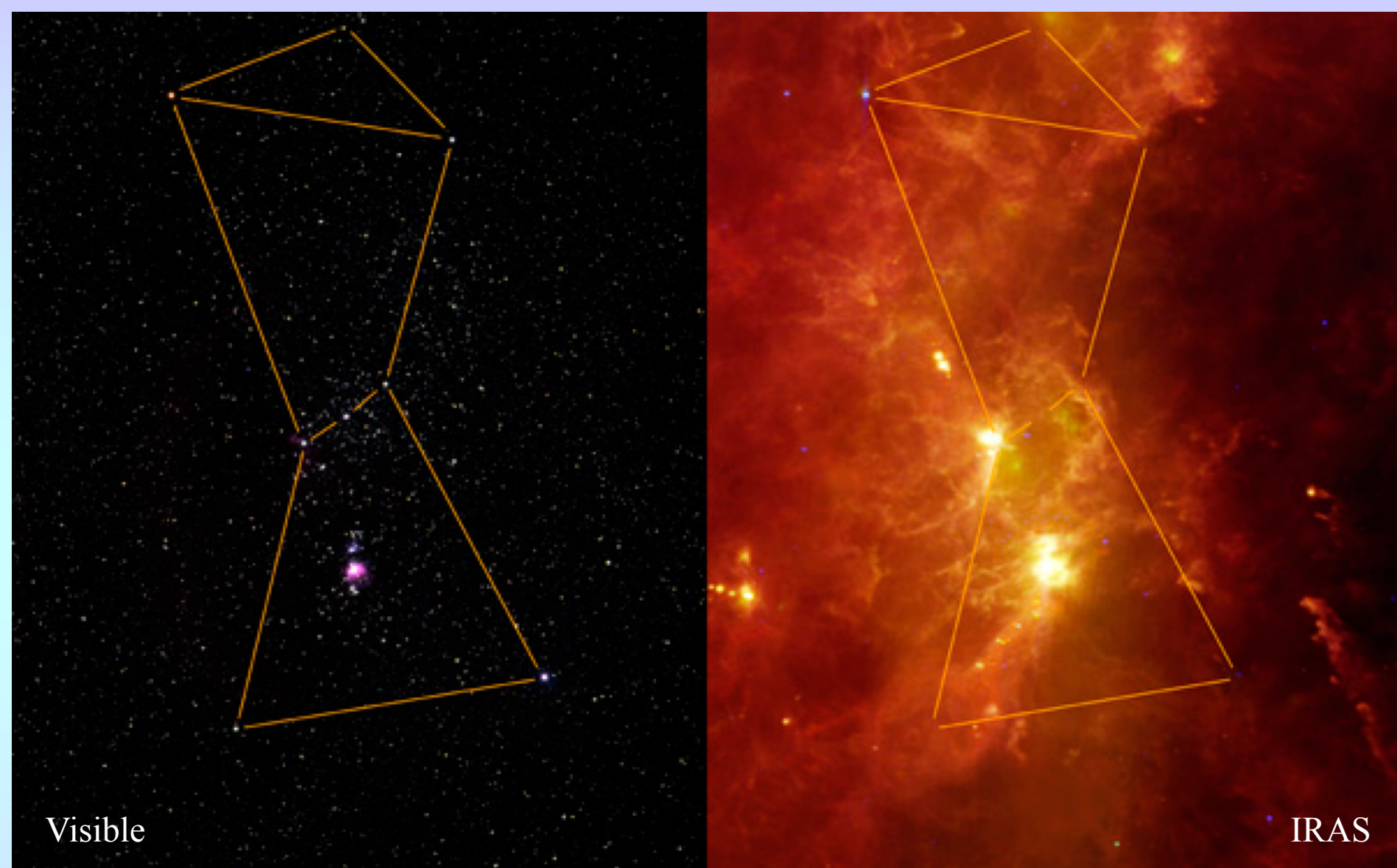# Star Formation

Star formation begins in Giant Molecular Clouds (GMCs). The Milky Way has several thousand of these objects, each with masses of $10^4\ M_\odot < M < 10^7\ M_\odot$, and sizes between 10 and 100 pc.

Although the average density of these clouds is $\sim 100\ \text{cm}^{-3}$, these objects are very clumpy, with large numbers of colder, dense cores.

Orion is the one of the nearest (but not nearly the biggest) molecular cloud system. (It's not even in a spiral arm.)
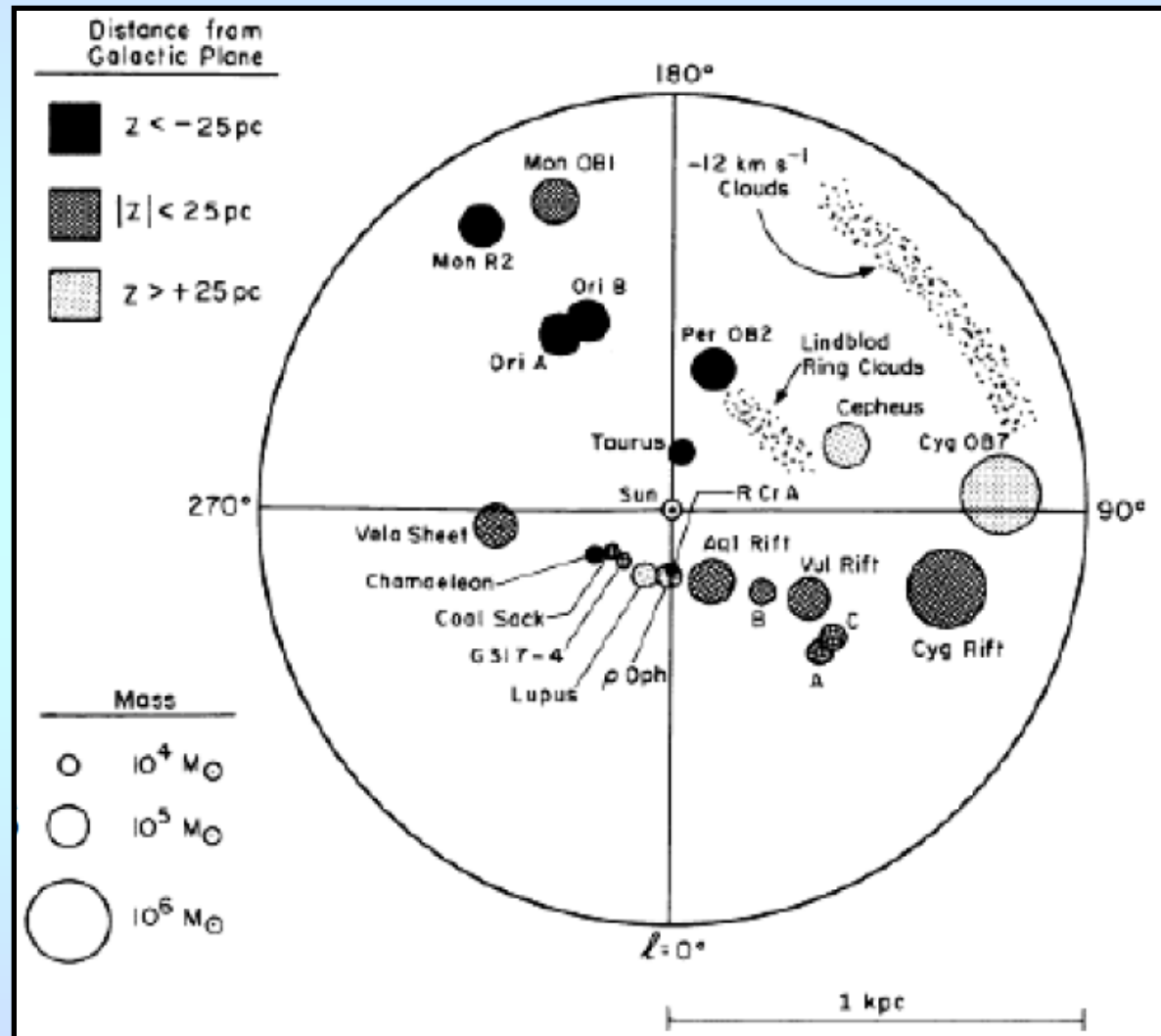
Visible

IRAS

Orion looks very different in the infrared compared to the optical.

The Nearest Star Forming Regions

Taurus is the nearest site of on-going star formation (though it is primarily forming low-mass stars.)

The nearest massive star formation is in Orion.

The nearest major star-forming complex is in Cygnus OB7 (in the Cygnus spiral arm).

Virial Theorem for Gaseous Systems

Assume you have a gravitationally bound system made up of an ideal gas in hydrostatic equilibrium. In the case of monotonic gas particles, the internal energy of this system, is

$$E_i = \int_0^{\mathcal{M}_T} u \, d\mathcal{M} = \int_0^{\mathcal{M}_T} \frac{3}{2} \frac{N_A}{\mu} k \, T \, d\mathcal{M}$$

If we substitute in the ideal gas law, this becomes

$$P = \frac{\rho N_A}{\mu} k \, T \implies E_i = \int_0^{\mathcal{M}_T} \frac{3}{2} \frac{P}{\rho} \, d\mathcal{M}$$

Now take the equation of hydrostatic equilibrium, multiply by $4 \, \pi \, r^3$, and integrate over the entire cloud

$$\int_0^R \frac{dP}{dr} \cdot 4\pi r^3 dr = - \int_0^R \frac{G\mathcal{M}(r)}{r} \rho \cdot 4\pi r^2 dr$$

Virial Theorem

When integrated by parts, the left side of this

$$\int_0^R \frac{dP}{dr} \cdot 4\pi r^3 dr = P(r)\, 4\pi r^3 \Big]_0^R - \int_0^R 12\pi r^2 P\, dr$$

So

$$P(R)\, 4\pi R^3 - \int_0^R 12\pi r^2 P\, dr = -\int_0^R \frac{G\mathcal{M}(r)}{r}\rho \cdot 4\pi r^2 dr$$

The first term on the left side goes away, since the pressure at the surface is zero, and the right side of the equation is just the total gravitational potential of the cloud.   Thus

$$\int_0^R 12\pi r^2 P dr = 2\int_0^R \frac{3}{2}\, P \cdot 4\pi r^2 dr = -E_{\mathrm{grav}}$$

Or, since $dM = 4\,\pi\,r^2\,\rho\,dr$

$$2\int_0^{\mathcal{M}_T} \frac{3}{2}\frac{P}{\rho} dM = -E_{\mathrm{grav}} \Longrightarrow 2\, E_i + E_{\mathrm{grav}} = 0$$

Virial Theorem

Note that the result of this simple derivation, $2\,E_i + E_{grav} = 0$ does not depend on $M(r)$, $\rho(r)$, or $T(r)$, and can be generalized for other equations of state. For an ideal gas

$$P = \frac{\rho N_A}{\mu} k\,T = \frac{2}{3}\,\rho\,u$$

but more generally, we can write $P = (\gamma - 1)\,\rho\,u$, where $\gamma = 5/3$ for an ideal gas. Under this law, the internal energy becomes

$$E_i = \int_0^{\mathcal{M}_T} \frac{1}{\gamma - 1} \frac{P}{\rho}\,d\mathcal{M}$$

And the virial theorem becomes

$$3(\gamma - 1)E_i + E_{\mathrm{grav}} = 0$$

Virial Theorem

Finally, let's consider the cloud's total energy, $W = E_i + E_{grav}$.

$$W = -\frac{E_{\text{grav}}}{3(\gamma - 1)} + E_{\text{grav}} = \frac{3\gamma - 4}{3\gamma - 3} E_{\text{grav}}$$

Note the implication of this equation. Because the system must have a non-zero temperature, it must radiate some of its energy into space. Thus, through energy conservation

$$\mathcal{L}_T + \frac{dW}{dt} = 0 \implies \mathcal{L}_T = -\frac{3\gamma - 4}{3\gamma - 3} \frac{dE_{\text{grav}}}{dt}$$

This means that as the cloud radiates, its gravitational energy will get more negative, but this decrease will be less than the energy radiated. The remaining energy will go into heating the cloud. In the case of an ideal gas, half the energy radiated will go into E_{grav}, the other half into E_i.

Note also that as long as $\gamma > 4/3$, $W > 0$. If $\gamma < 4/3$, the total energy will be negative, and the system will collapse.

Jeans Criterion

A cloud will collapse if the gravitational potential is stronger than its thermal (and magnetic) support. In other words, $E_{grav} > -3\,(\gamma - 1)\,E_i$. As we just saw, the internal energy is

$$E_i = \int_0^{\mathcal{M}_T} \frac{1}{\gamma - 1} \frac{P}{\rho}\, d\mathcal{M} = \int_0^{\mathcal{M}_T} \frac{1}{\gamma - 1} \frac{1}{\mu m_H} kT\, d\mathcal{M}$$

For simplicity, let's take a uniform density, isothermal cloud. For such a cloud to collapse

$$E_{\text{grav}} = -\int_0^R \frac{G\mathcal{M}(r)}{r} d\mathcal{M} = -\frac{3}{5} \frac{G\mathcal{M}^2}{R} > 3\,(\gamma - 1)\,E_i = \frac{3}{\mu m_H} kT\mathcal{M}$$

or if we substitute density for radius via $\quad \rho = \dfrac{\mathcal{M}}{\frac{4}{3}\pi R^3}$

$$M_J > \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho}\right)^{1/2}$$

Jeans Criterion

Plugging in numbers, this becomes

$$M_J > \left\{\frac{5kT}{G\mu m_H}\right\}^{3/2} \left\{\frac{3}{4\pi\rho}\right\}^{1/2} \approx 10^5 M_\odot \left(\frac{T}{100 \text{ K}}\right)^{3/2} \left(\frac{n}{\text{cm}^{-3}}\right)^{-1/2}$$

This is the Jeans mass. If we re-write the criterion in terms of the sound speed, $c_s = (\gamma P/\rho)^{1/2}$, and assume an ideal, monotonic gas ($\gamma = 5/3$), gravity will overcome the thermal energy when

$$\mathcal{M}_J > \frac{9}{2}\frac{c_s^3}{G^{3/2}\sqrt{\pi\rho}}$$

Similarly, we can replace mass with density to derive the Jean's length

$$R_J > \left(\frac{15kT}{4\pi G\mu m_H \rho}\right)^{1/2} = \frac{3}{2}c_s\left(\frac{1}{\pi G\rho}\right)^{1/2}$$

All scales larger than this are unstable to collapse.

Jeans Criterion

Another way of looking at the collapse problem is to compare the timescale for free fall collapse to the timescale for a pressure wave to propagate across the cloud and restore equilibrium.

In the absence of gas or magnetic pressure, the free-fall collapse time is $\tau_{ff} \sim (1 / G \rho)^{1/2}$, while that for a pressure wave is simple $\tau_s \sim R / c_s$. If the free-fall time is less than the time it takes for a pressure wave to cross the system, then

$$\mathcal{M}_J > \frac{c_s^3}{\sqrt{\rho\, G^3}}$$

Note that the Jeans Criterion is somewhat of a swindle, since it assumes that the gas immediately outside the cloud is static. (In fact, it will be collapsing as well.) Note also that for a better estimate, one needs to include external and magnetic pressure in the virial theorem, i.e.,

$$2\, E_i + E_{grav} + B - 3\, P_{ext}\, V = 0$$

Fragmentation and Accretion

As gas collapses in a cloud core, the density increases, causing the Jeans mass to decrease. This leads to fragmentation, as smaller regions of the cloud are pushed over the Jeans mass.

• The increase in density causes the cloud to become opaque to IR photons. The trapped energy heats the cloud, increases the gas pressure, and brings the system into hydrostatic equilibrium.

• Due to the cloud's angular momentum, an accretion disk is formed. From the virial theorem, half the energy of accretion heats the star, half is radiated, so

$$\mathcal{L}_{\text{acc}} = \frac{GM\dot{M}}{2R}$$

Dimensions: 82500. AU   Time: 0. yr

Log Column Density [g/cm²]

-1.4   -1.2   -1.0   -0.8   -0.6   -0.4   -0.2   0.0

Matthew Bate
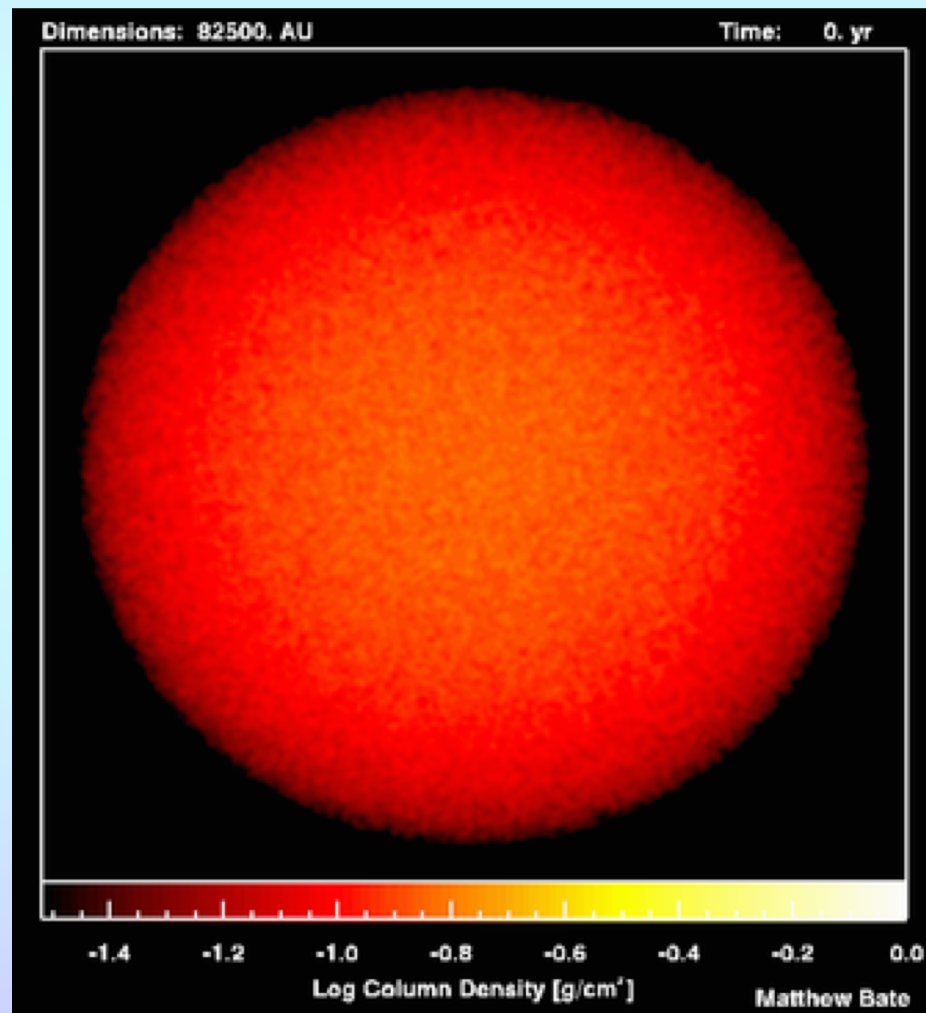
Collapse and Fragmentation

• In general, the timescale for accretion, $\tau_{acc} \sim M / \dot{M}$, is shorter than the protostar's thermal timescale. The protostar cannot thermally adjust to the added energy, and therefore heats up adiabatically.

• Eventually, the protostar becomes hot enough to disassociate molecular hydrogen. When this happens, the energy input does not go into heating the gas, but disassociating the hydrogen. This means that the specific heat of the protostar becomes very small, $\gamma < 4/3$, and, through the virial theorem, the star must collapse on a dynamical timescale. This collapse releases energy, which goes into further H_2 disassociation (rather than heating the gas). Very quickly, all the molecular hydrogen is destroyed, and the protostar settles into a new hydrostatic equilibrium. Similar episodes occur when the temperature becomes hot enough to ionize hydrogen and helium, $T \sim 10^4$ K.

Herbig-Haro Objects

• Bipolar outflows, powered by the accretion, break through where the disk has the lowest density (out the poles). These patches of nebulosity are called Herbig-Haro objects.

Jets from Young Stars · HH1/HH2   HST · WFPC2

PRC95-24c · ST ScI OPO · June 6, 1995 · J. Hester (AZ State U.), NASA
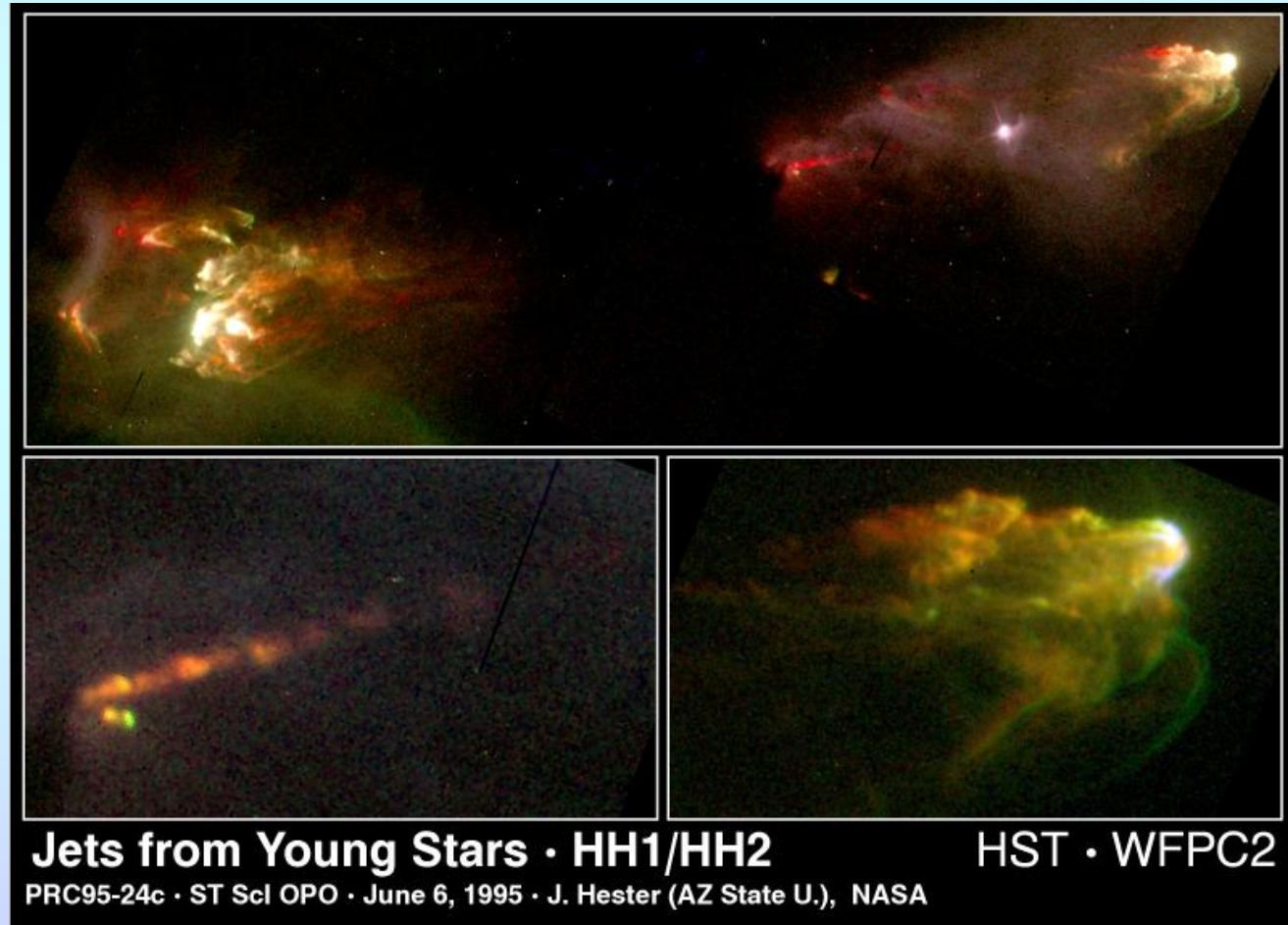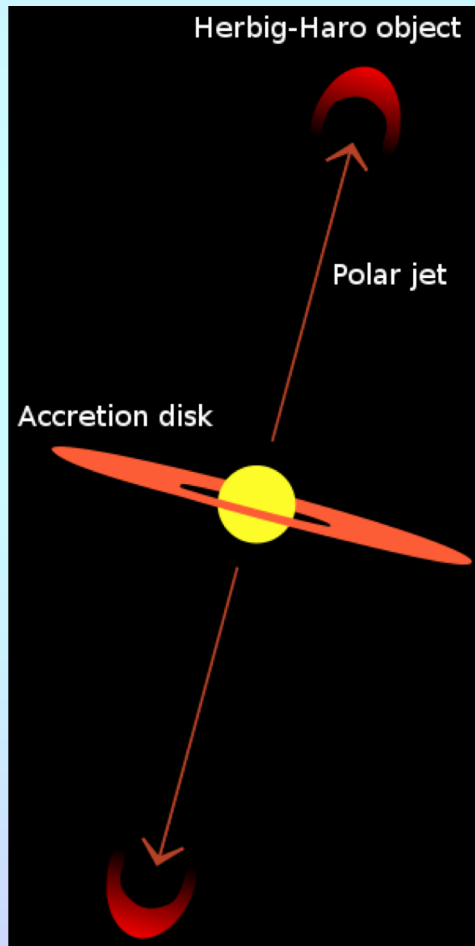
Young Stellar Objects (YSOs)

• Finally, accretion slows down, and the star creates energy via gravitational collapse. The pre-main sequence phase begins, where, from the virial theorem, the interior temperature increases as

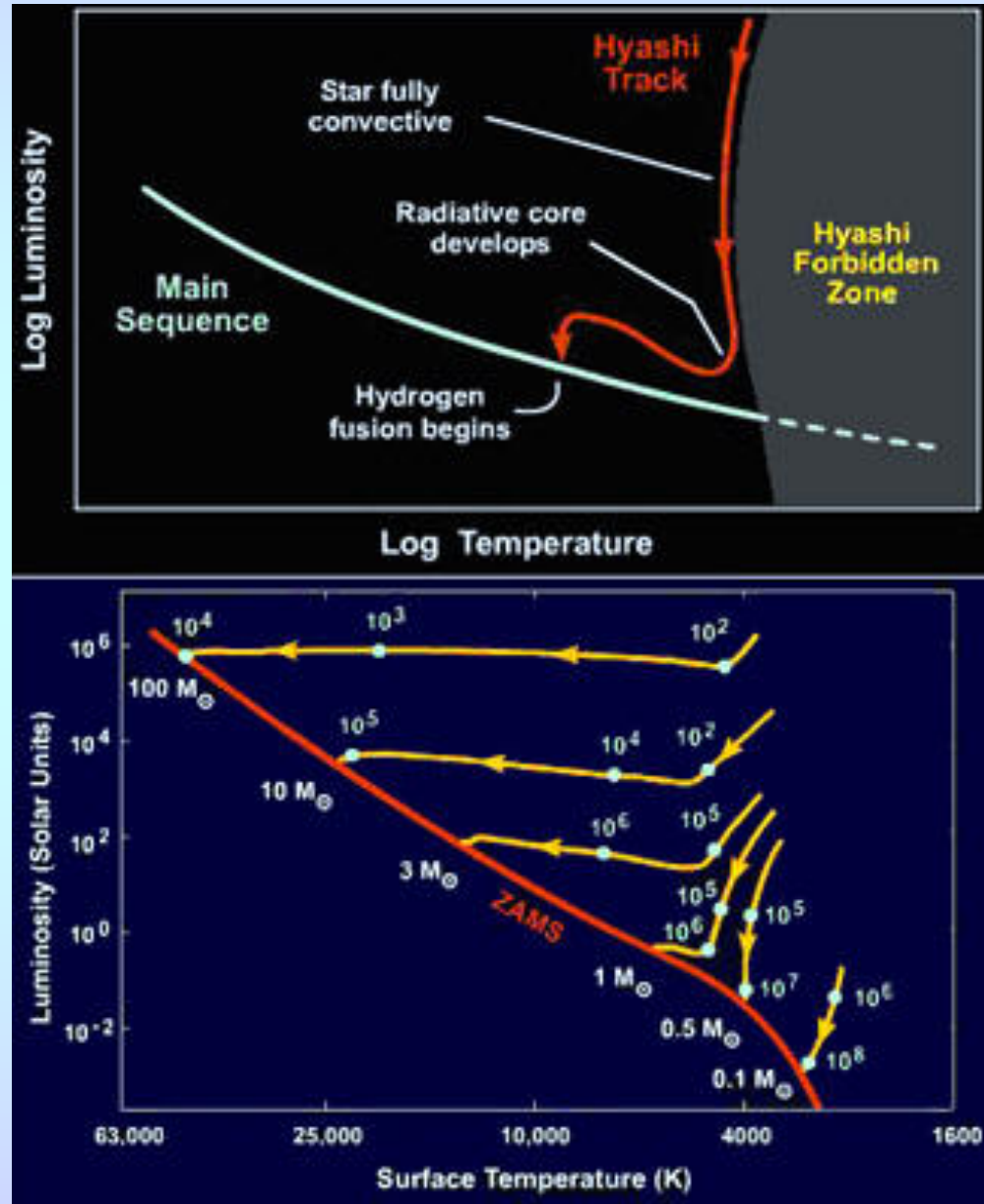$$\frac{G\mathcal{M}}{R} \sim kT \implies$$

$$T \sim M^{2/3}\rho^{1/3}$$
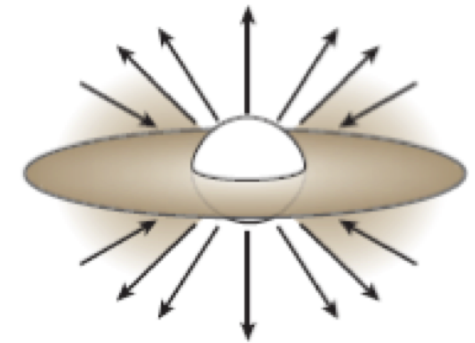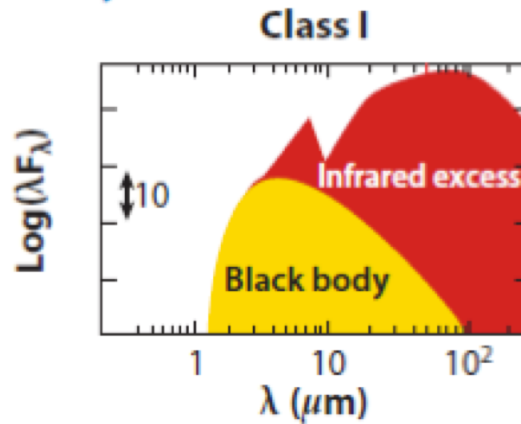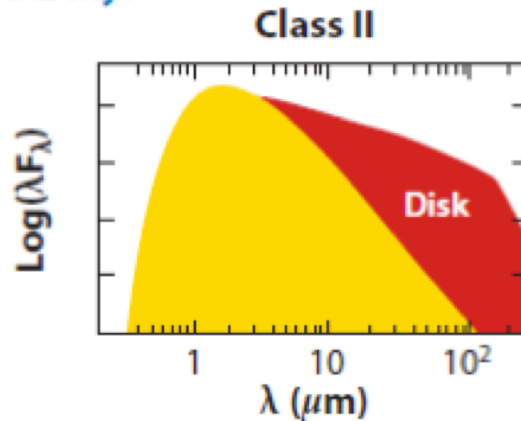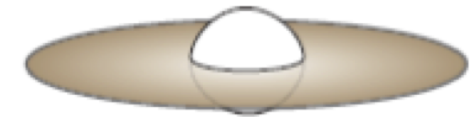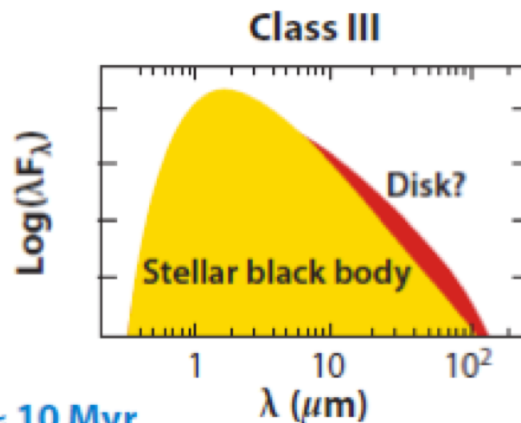
Pre-Main Sequence Evolution

• Prior to hydrogen ignition, the star simply evolves via contraction, on a thermal timescale

$$t_{KH} = \frac{G\mathcal{M}^2}{R\mathcal{L}}$$

Evolution proceeds nearly vertically, down the Hayashi track, which, by definition, is the location of fully convective stars. (In other words, $\mathcal{L}$ changes, but T is nearly constant.)
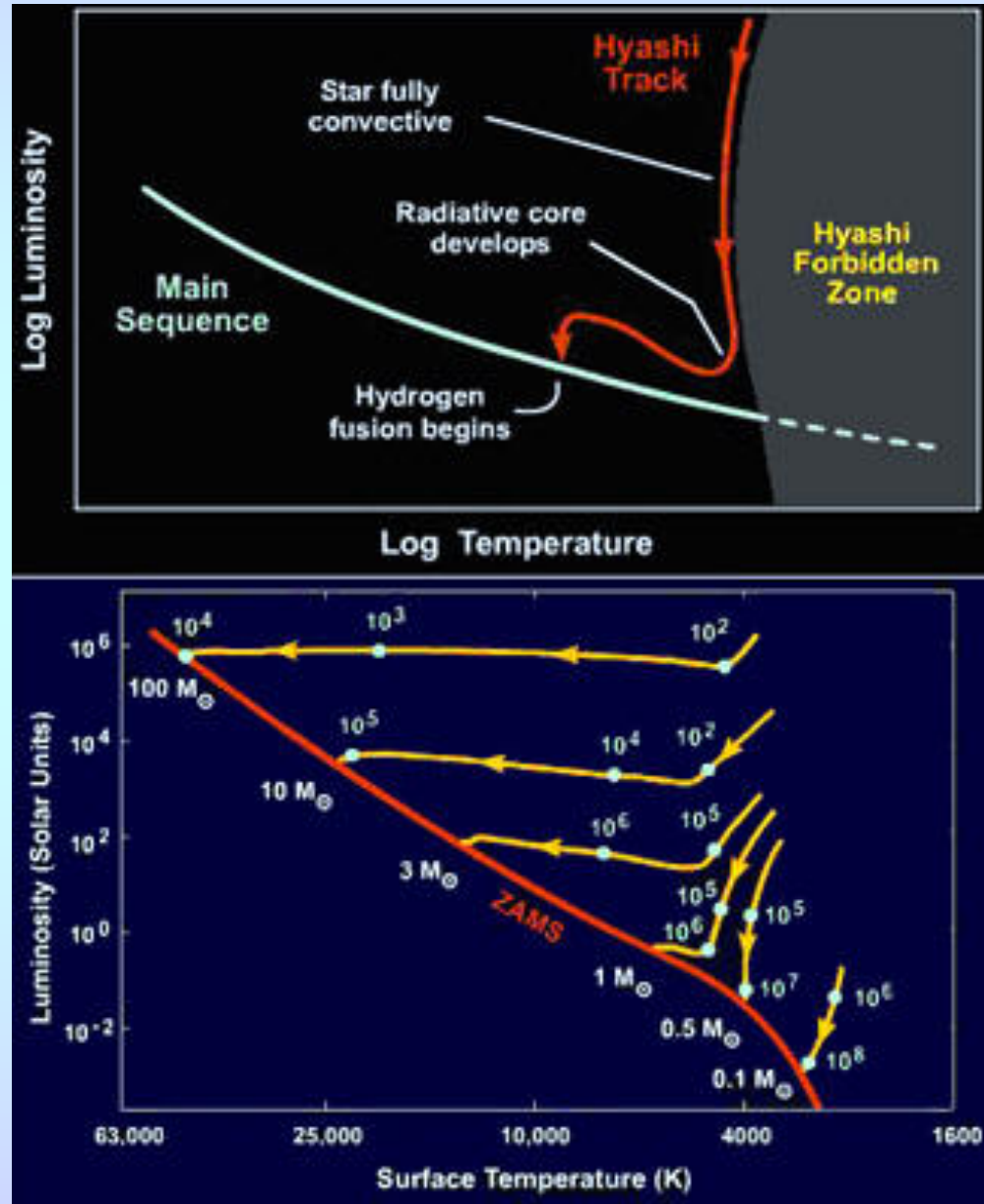
Pre-Main Sequence Evolution

• Prior to hydrogen ignition, the star simply evolves via contraction, on a thermal timescale

$$t_{KH} = \frac{G\mathcal{M}^2}{R\mathcal{L}}$$

Eventually, the protostar heats up until a radiative zone is formed in the core. This new mechanism of energy transport changes the protostar's structure and evolution; instead of moving vertically, it moves horizontally on the HR diagram, i.e., at constant $\mathcal{L}$ but changing T.
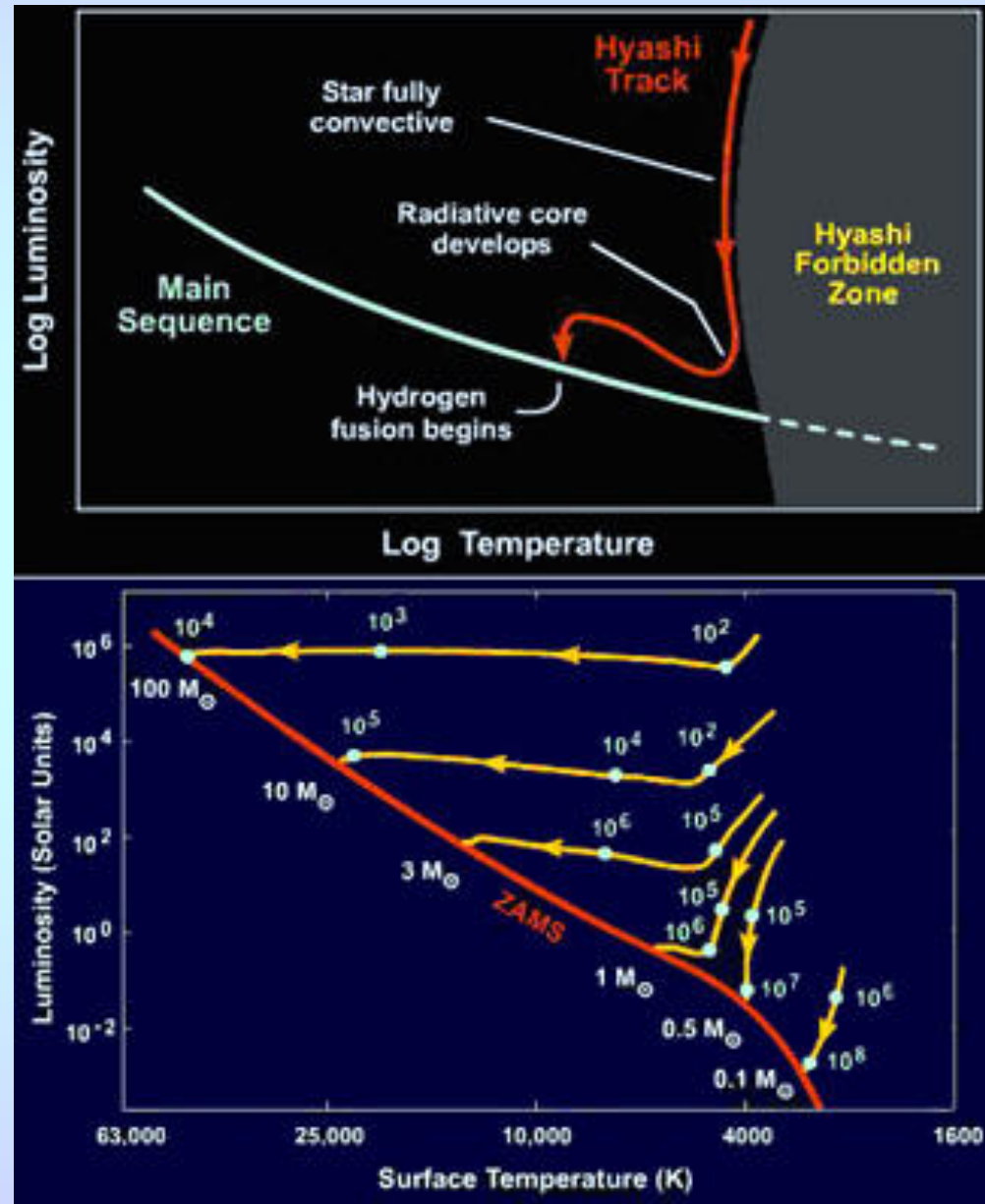
Pre-Main Sequence Evolution

• Prior to hydrogen ignition, the star simply evolves via contraction, on a thermal timescale

$$t_{KH} = \frac{G\mathcal{M}^2}{R\mathcal{L}}$$

Note that due to the thermal timescale (and the strong dependence of luminosity with mass), high mass stars will evolve much more quickly than low mass stars.

Aside: Stellar Rotation

The Sun does not rotate as a solid body: its equator rotates once every 25 days, while regions near the poles rotate every 30 days. There is evidence that most/all stars with convective envelopes behave the same way.
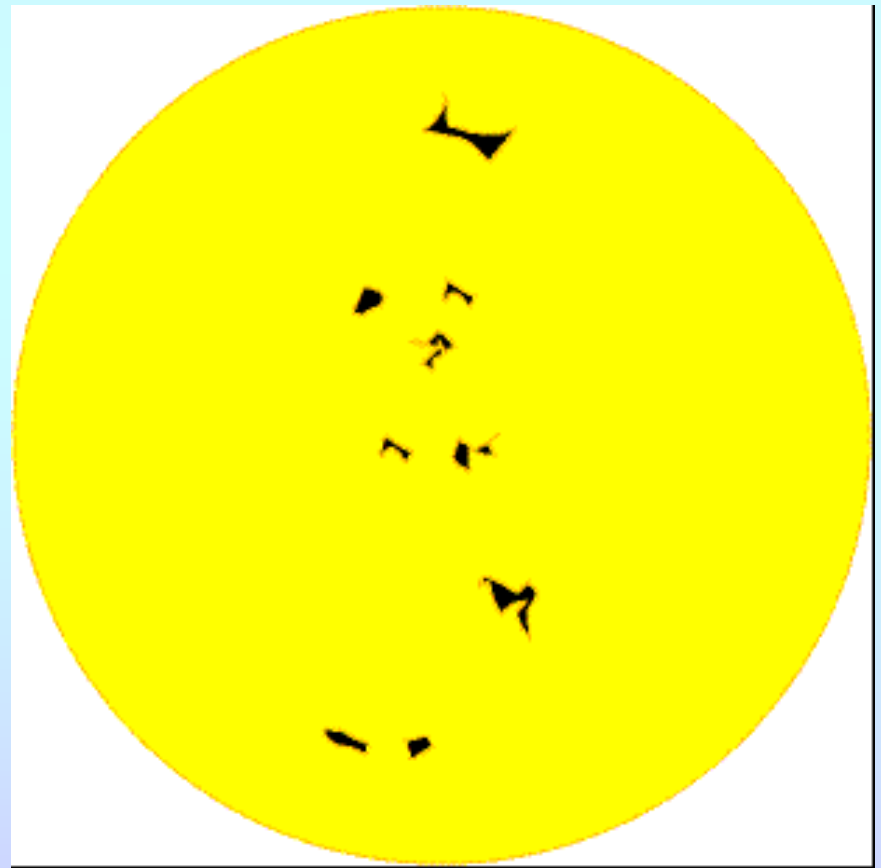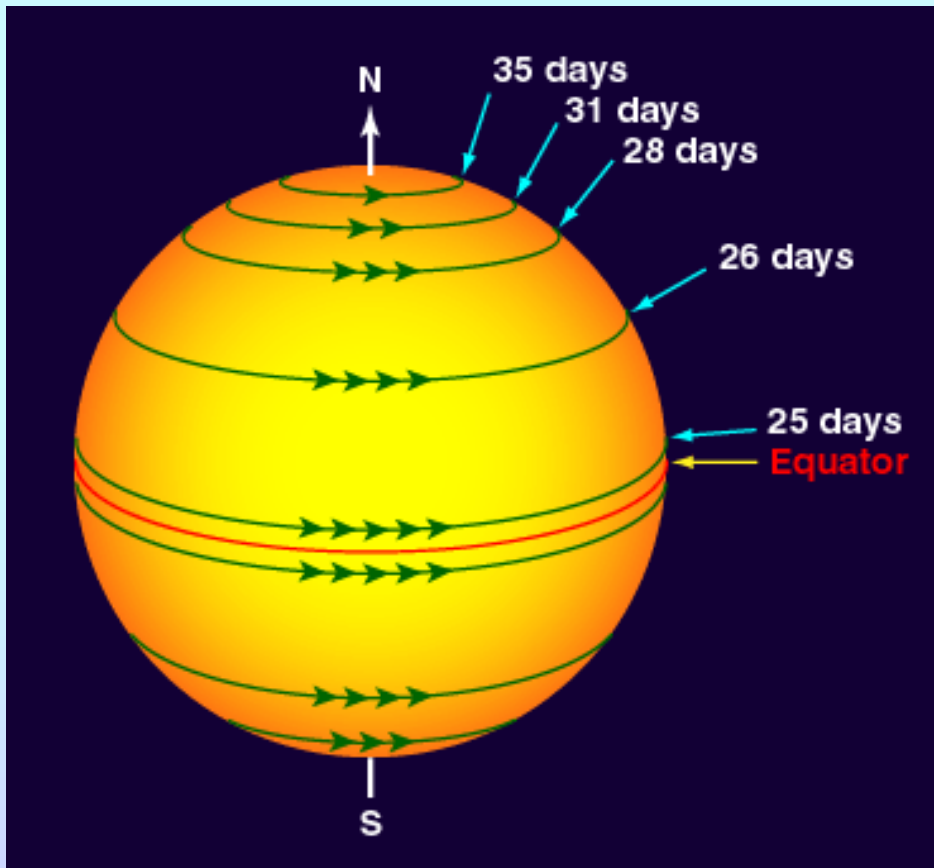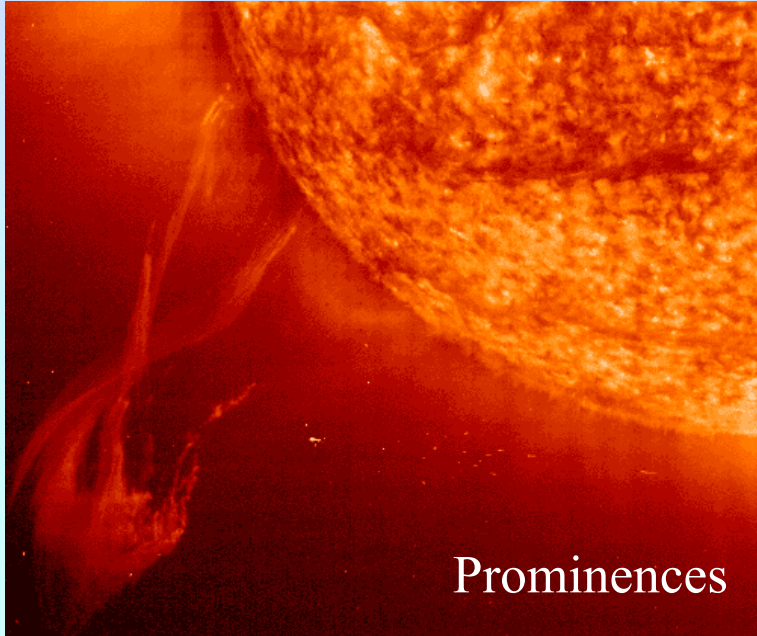
The Sun's Magnetic Field

Imagine the Sun as a bar magnet, with magnetic field lines cutting through it. The field lines are attached to the Sun.
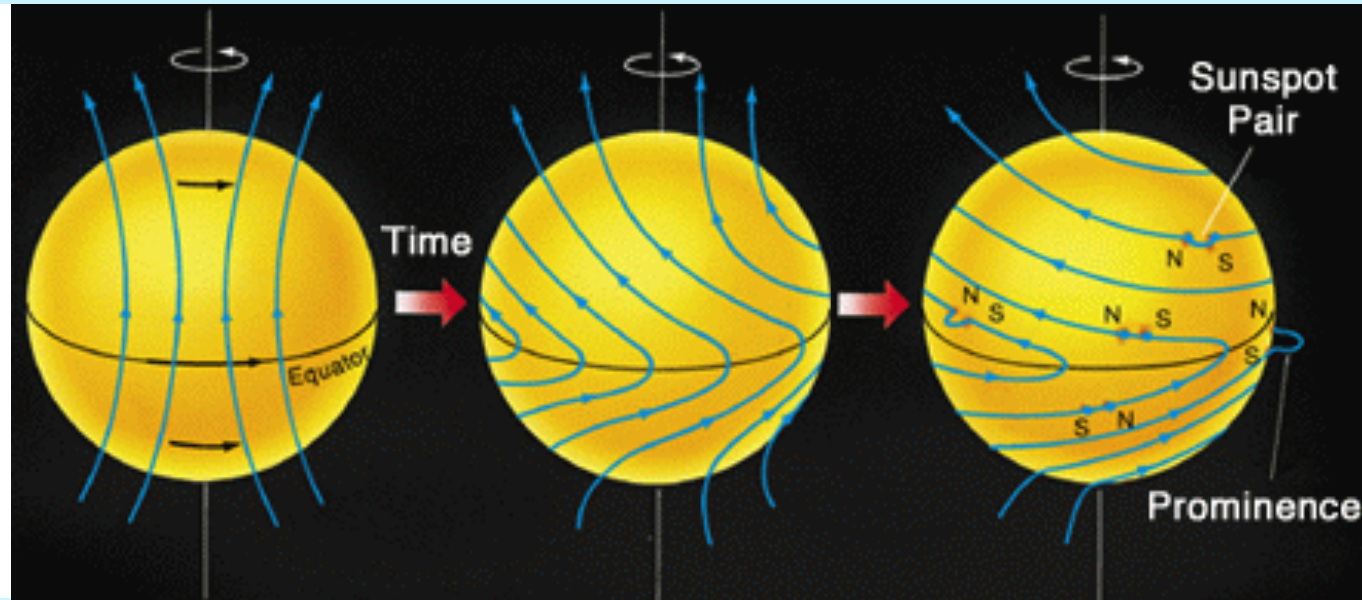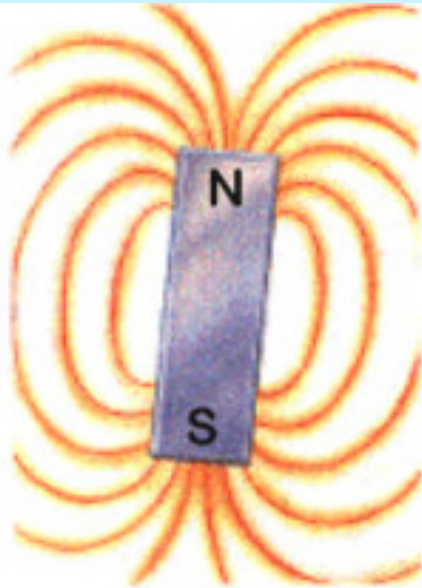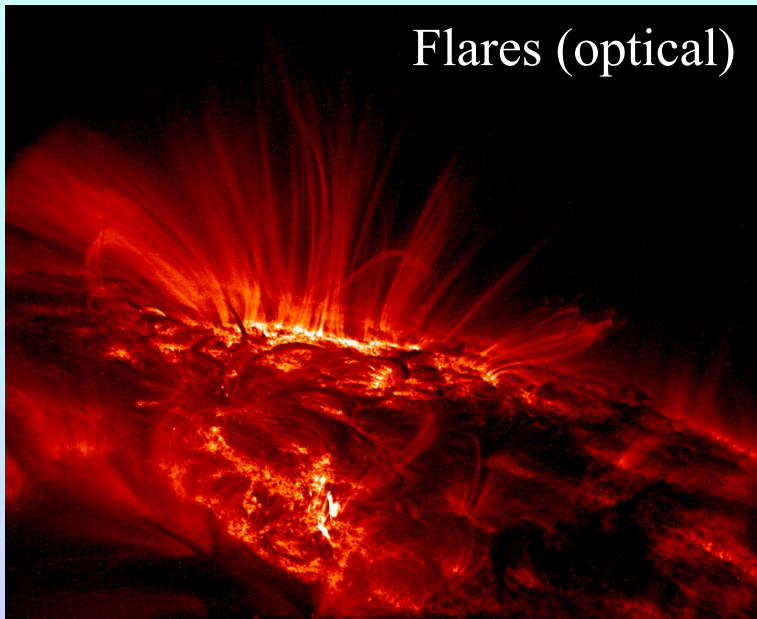

After a while, differential rotation stretches and stresses the field lines. Kinks develop. Eventually, the lines are stretched to the breaking point. When they break, the lines reconnect and energy is released.
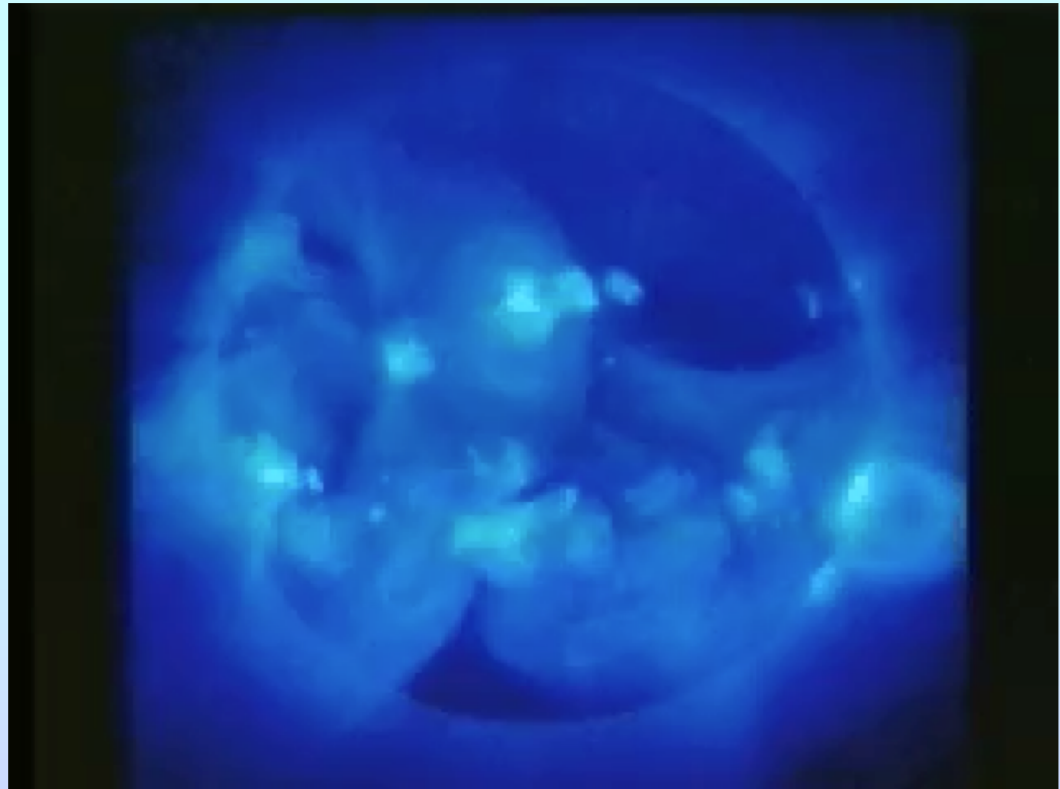
Stellar Activity

Prominences

Flares (optical)

When the magnetic field lines reconnect, the results are sunspots, prominences, and flares.
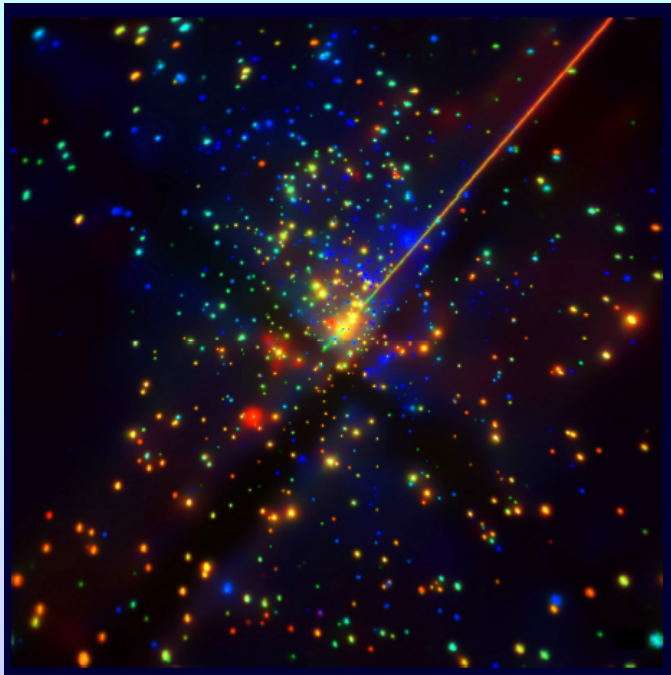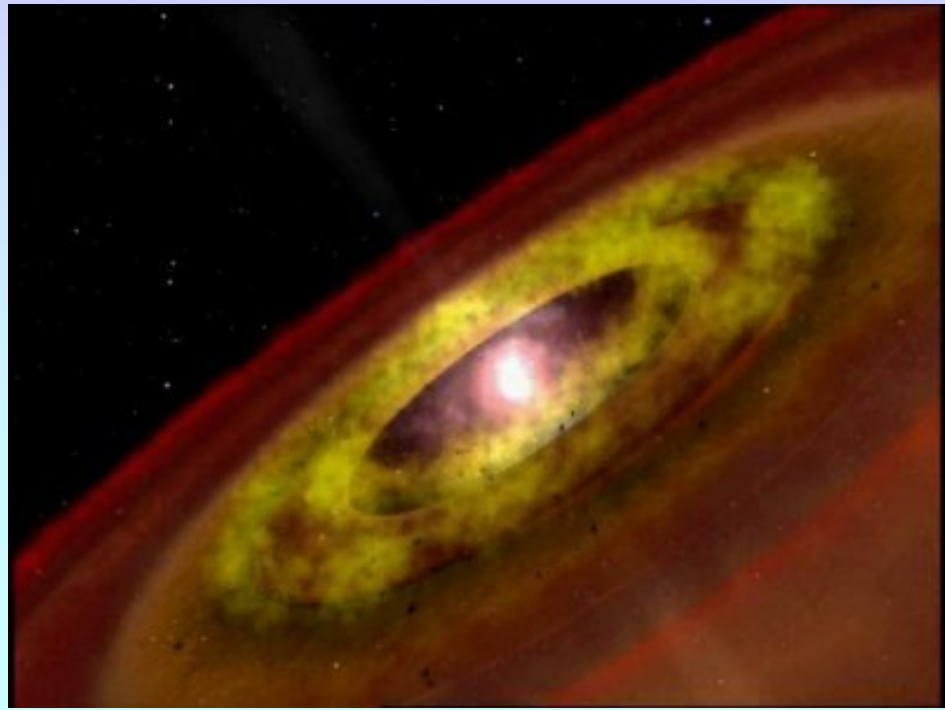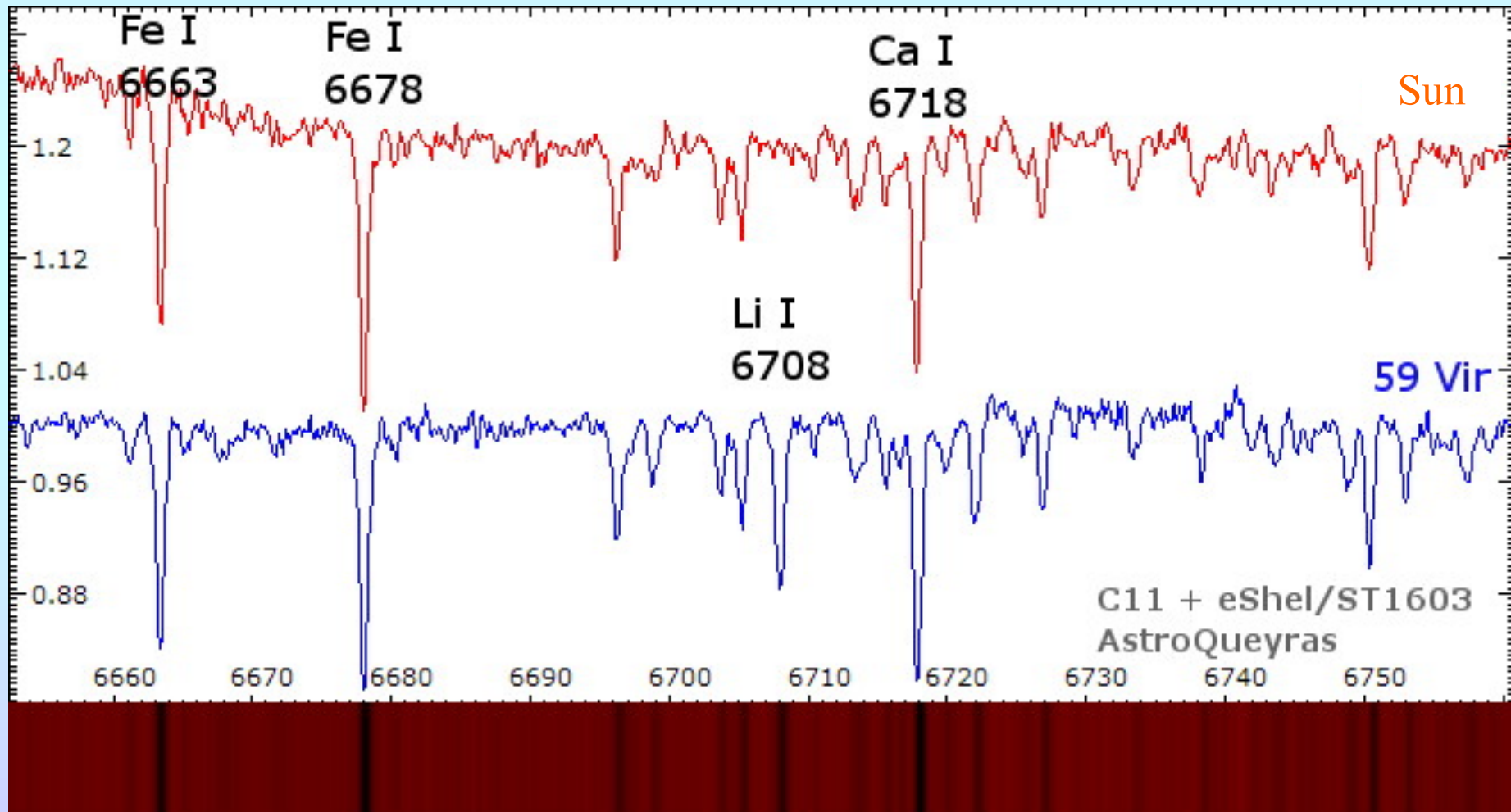
T Tauri Stars

Low mass, variable, gravita-tionally contracting objects are called T Tauri stars. Based on the strength of their Hα emission (which presumably comes from the disk), they are sub-classed as "Classical", "Weak-Lined", and "Naked".

Because T Tauri stars are young, they are rotating relatively fast, and because they have convective envelopes, their magnetic fields can quickly become wrapped up, causing violent flares. Young stars are often X-ray sources (and the X-ray emission can last longer than the disk).

Lithium and Young Stars

In stars with convective envelopes, brittle species like lithium will be destroyed by the high temperatures at bottom of the convective layer. The presence of lithium is thus an age indicator: young, low-mass stars have Li absorption lines.

Types of Young Stars

T Tauri Stars: F, G, K, and M stars with Hα and excess IR emission (presumably from their disk)

FU Orionis Stars: T Tauri stars with extreme variability (both in brightness and spectral type) presumably from flares

Herbig Ae Be Stars: A- and B-type counterparts to T Tauri stars, with Hα emission and IR excess

UX Orionis Stars: Herbig Ae Be stars with extreme variability (in color and magnitude) due to changes in the extinction caused by dust in their disks